DESIGN AND DEVELOPMENT OF HIGH SENSITIVITY SENSOR FOR FINGER TRACKING IN PIANO PLAYING

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DECLARATION

I hereby declare that the material in this thesis is my own except for quotations, equations, summaries and references, which have been duly acknowledged.

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CERTIFICATION

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ABSTRACT

The art of planning the movement of hands in order to produce the desired sound of the piano is one of the important part of piano technique. Various researches have attempted to unveil the technique of virtuoso pianists using technologies. These researches employ different types of sensors in order to capture motion data in piano playing. However, one area in these researches have been under-represented, which is the finger position of a musician while playing the musical instrument. In piano technique, it is very important to study the finger position that could land on any position along the surface of one single key. Researches that embark on this area face a common problem, the sensors used in these researches are short in range and directly in contact with the pianist, which causes a change of piano playing experience. To avoid obstruction to the pianist, the finger tracking sensor should be placed away from the keyboard and track human finger across a set of wooden piano keys with $13\,cm$ thickness. However, current technologies of capacitive finger tracking emphasizes either on near proximity sensing or remote gesture recognition, where both of them do not focus on accurate remote positional tracking that is required in this application. The range limitation of the current sensors is mainly affected by circuit design and size of electrodes. Concluding the challenges, a high sensitivity finger tracking sensor is proposed. A series of researches and comparing are carried out to select a high sensitivity capacitive sensing method with low noise. Upon selecting the sensing method, circuit modifications and components parameters tuning are applied. This includes minimizing stray capacitance and filtering noise. In addition to this, the sizes and arrangements of electrodes are optimized where electrodes are coupled with wooden keys to increase sensitivity of the sensor. The final signals from the sensor are digitalized and trained using artificial neural network to obtain positional data. This prototype sensor is developed to track different position of the fingers on five keys of the piano. To validate the design, 500 sets of independent input data with known output position were used to test the network. The output shows that the average error between the test set and the desired target is $7\,mm$, which translate to 83.79% accuracy. The error and accuracy from the output is reasonably good for all data set. To summarise, this research presents the design and development of a high sensitivity finger tracking sensor through sensor hardware design and signal processing. The outcome from this work could be applied to researches that require detection of minute capacitance induced by human finger.

ABSTRAK

MEREKA BENTUK DAN MEMBINA SENSOR KEPEKAAN TINGGI UNTUK MENGESAN KEDUDUKAN JARI SEMASA BERMAIN PIANO

Seni merancang pergerakan tangan untuk menghasilkan bunyi yang diingini di piano adalah salah satu bidang penting untuk teknik piano. Pelbagai kajian telah cuba untuk menyelidik teknik pemain piano virtuoso menggunakan teknologi. Penyelidikan ini menggunakan pelbagai jenis sensor untuk mendapat data gerakan tangan semasa bermain piano. Walau bagaimanapun, satu bidang dalam penyelidikan ini kurang diselidikan, iaitu kedudukan jari ahli muzik semasa bermain alat muzik. Dalam teknik piano, kedudukan jari adalah penting kerana ia boleh berada di mana-mana kedudukan di sepanjang permukaan piano. Penyelidikan dalam bidang ini biasanya menghadpi masalah yang sama, sensor yang digunakan dalam penyelidikan ini adalah berjarak pendek dan menyentuh ahli pemain piano, ini mengganggu pengalaman bermain piano. Untuk mengelakkan halangan kepada pemain piano, sensor pengesan jari harus diletakkan jauh dari papan kekunci piano di bawah kayu dengan ketebalan 13 cm. *Walau bagaimanapun, teknologi pengesanan jari kapasitif terkini mementingkan sama ada pada sensor jarak pendek atau gerakan tangan untuk jarak jauh sahaja, kedua-dua ini tidak mementingkan kedudukan jari bagi sensor jarak jauh, seperti yang diperlukan dalam aplikasi ini. Jarak sensor dipengaruhi oleh reka bentuk litar dan saiz elektrod. Untuk menangani masalah ini, sensor pengesan jari kepekaan tinggi dicadangkan. Satu siri penyelidikan dan perbandingan daijalankan untuk memilih kaedah sensor kapasitif bersensitiviti tinggi dengan gangguan rendah. Dalam pemilihan kaedah pengesanan, pengubahsuaian litar dan parameter komponen dilakukan. Ini termasuk mengurangkan kapasitansi gangguan dan penapisan. Di samping itu, saiz dan susunan elektrod dioptimumkan di mana elektrod digabungkan dengan bahagian kekunci piano untuk meningkatkan kepekaan sensor. Isyarat dari sensor diproses dengan menggunakan rangkaian neural buatan untuk memerolehi data kedudukan jari. Sensor prototaip ini dibina untuk mengesan kedudukan jari pada lima kekunci piano. Untuk mengesahkan reka bentuk ini, 500 set data input dengan kedudukan keluaran yang telah diketahui digunakan untuk menguji rangkaian tersebut. Output pengujian menunjukkan bahawa purata kesilapan adalah 7 mm, iaitu reka bentuk ini mempunyai kejituan 83.79%. Kejituan dari output dianggap cukup baik untuk semua set data. Sebagai ringkasan, penyelidikan ini membentangkan reka bentuk dan pembinaan sensor pengesan jari kepekaan tinggi melalui reka bentuk perkakasan sensor dan pemprosesan isyarat. Hasil daripada kerja ini boleh digunakan untuk penyelidikan yang memerlukan pengesanan kapasitans yang kecil ounca dari jari manusia.*

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LIST OF ABBREVIATIONS

3D	Three Dimensional Space
ACT	Anatomically Correct Testbed
ADC	Analogue to Digital Converter
ANN	Artificial Neural Network
ARES	Advanced Research and Engineering Support
Bosendorfer SE System	Bosendorger Stahnke Engineering System
C	Capacitance
CCP	Capture / Compare / PWM Module
e-field	Electric field
EMG	Electromyogram
IDE	Integrated Development Environment
ISIS	ILOG Solution Implementaion Standard
LED	Light Emitting Diode
MATLAB	Matrix Laboratory
MSE	Mean Squared Error
PCB	Printed Circuit Board
PIC	Programmable Interrupt Controller
PICKit 2	A family of programmers for PIC microcontrollers made by Microchip Technology
PROTEUS	Profile Telemetry of Upper Ocean Currents
Q	Stored charge
USART/SCI	Universal Synchronous Asynchronous Receiver Transmitter Module

LIST OF SYMBOLS

(x, y)	–	Position of finger (cartesian coordinate)
Ω	–	ohm (resistance)
MHz	–	Megahertz
V	–	voltage

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CHAPTER 1

INTRODUCTION

1.1 Overview of Remote Finger Tracking Sensor for Piano

Musician had been striving to perfect the technique of musical instrument playing for centuries. Along with the advancement of technologies, a number of methods had been developed to capture the movement of musical instrument players in order to analyze their technique. The mentioned technologies often fuse sensors with the musical instrument, creating augmented musical instruments. By definition, augmented musical instruments are created by the addition of sensors to existing acoustic or electric instruments (Dan and Mark, 2011). These sensors collect various types of input from the musical instrument players, not only tracking the movement of the players, but also allowing them to control additional digital audio effects or sound synthesis processes through their gestures. These methods offer numerous possibilities for musical performances (Otso *et al.*, 2009). For these augmented instruments, one area had been underrepresented, which is finger positioning strategy applied by professional musicians while playing musical instruments (Tobias and Gerhard, 2013).

The area of interest of this research is piano playing movement analysis, more specifically the fingers position of a pianist. These information is crucial for technique analysis because there is a distinct difference in hand posture and movement strategy of the arm between professional and amateur pianists (Furuya *et al.*, 2011).

1.2 The Need for the Research

One main reason fingers land differently on the keyboard each time a pianist play the piano is because the five fingers of a human hand have different length as shown in Figure 1.1. To achieve efficient movements, a pianist often employs different techniques to move his or her hands so that they could perform complicated pieces of music.

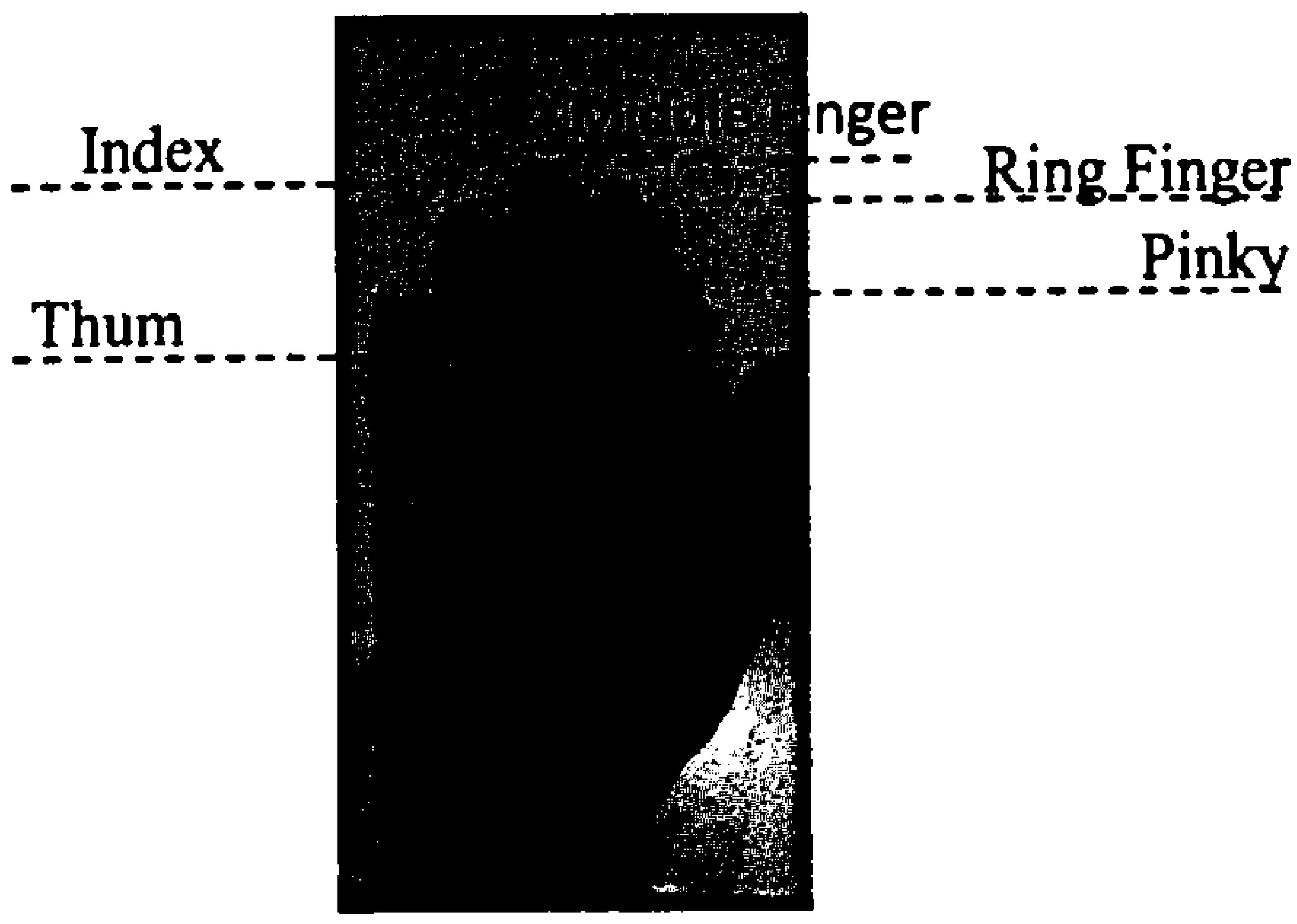

Figure 1.1 : Human fingers with different lengths.

The keyboard of the piano had been designed to accommodate the different lengths of the fingers. Unlike computer keyboard that only consists of one type of button with uniform shape, the piano keys consist of keys with different shapes, where each key has a relatively big surface for a pianist to press. Furthermore the keys also have different heights as shown in Figure 1.2. One main feature both the white and black keys have in common is it is very long and a pianist could choose to play at any part of the long surface of the key. Besides that, a pianist can also choose to play anywhere on the wider part of the white keys.

Figure 1.2 : Different surface shape of piano keys.

Figure 1.3 shows an example of user playing at different positions of the same key. Depending on what the pianist wish to achieve, whether is to create a desired sound from the piano or just simply choosing a more efficient movement to reach the key, a pianist often varies the finger landing position on the key.

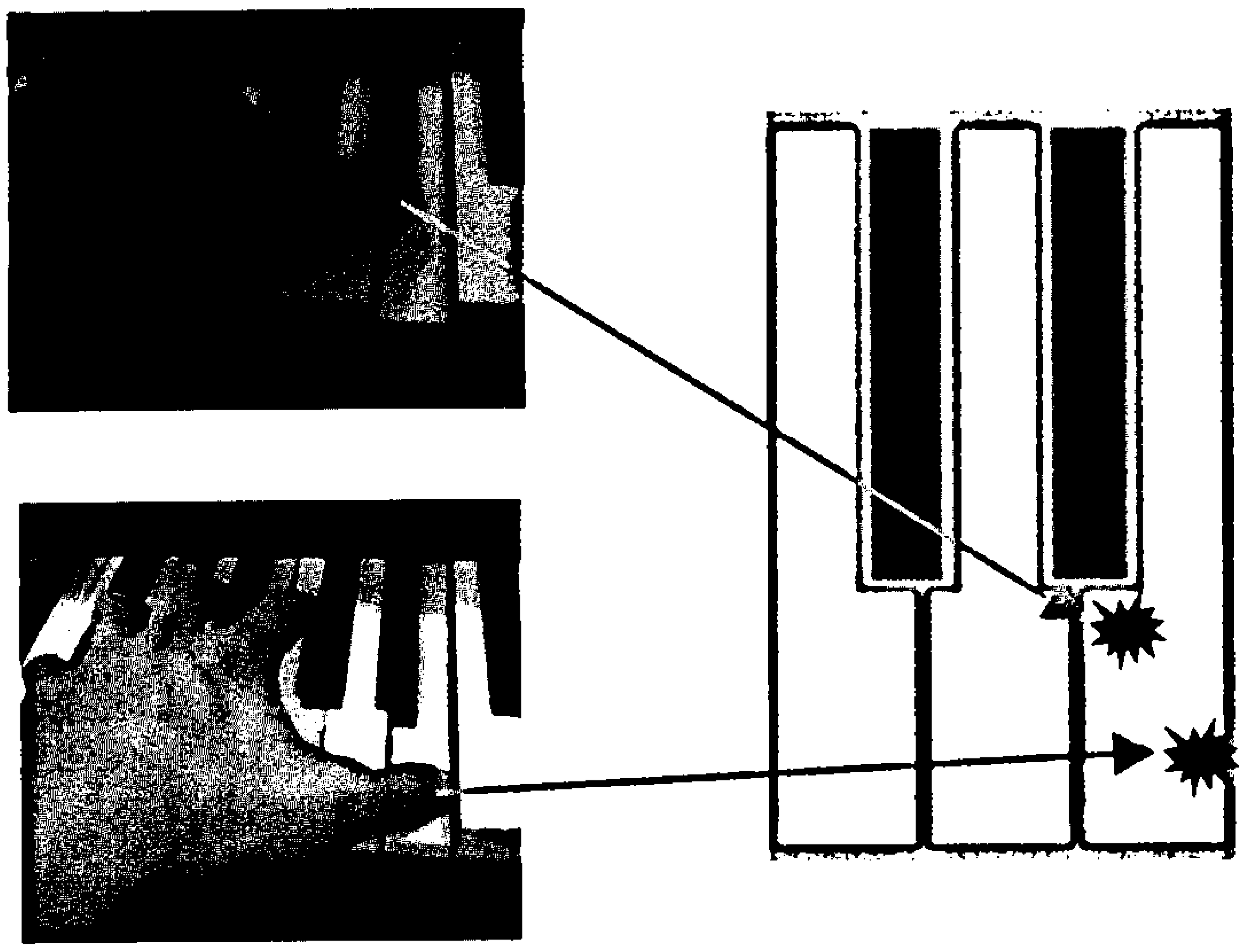

Figure 1.3 : Playing at different positions on the white key.

1.3 Contactless Remote Finger Tracking Sensor for Piano

Various researches such as Furuya *et al.* (2011) had attempted to unveil the technique of virtuoso pianists using technologies which includes detecting the finger position on the piano and the dynamics of the sound produced. Although many researches have been conducted, one area had been underrepresented, which is the finger positioning strategy applied by professional musicians while playing musical instruments (Tobias and Gerhard, 2013). Researches that embark on this area employ different types of sensors in order to capture motion data of piano playing. They faced a common problem, the sensors used in these works are directly in contact with the pianist, in other words, this causes a change of piano playing experience. Since piano playing consists of very delicate interaction between the pianist and the piano, such change of experience may affect a pianist's performance. To circumvent this problem, a contactless sensor is proposed in this research that is developed using capacitive sensing method. The main reason capacitive sensing is proposed is because this sensing method possess the capability to remotely detect objects across obstacles. However, the resultant capacitance change caused by the finger is very faint especially when it is far from the capacitive sensor, this low signal could often be obscured by the environmental noise. Therefore, proper design need to be carried out for developing a contactless finger tracking sensor.

1.4 Problem Statement

Capacitive sensing has played an important role in human-computer interaction. Conventional design of typical capacitive sensors are limited by close proximity (Braun *et al.,* 2015) due to low capacitance signal between the sensor and human body. This is especially true for capacitive sensors designed to track the position of fingers, such as the capacitive sensing on mobile phones.

For finger position tracking application, multiple electrodes are arranged near to each other to track the position of the fingers by processing the signals received by the neighboring electrodes, similar to triangulation. The range limitation of finger position tracking capacitive sensor is mainly affected by the small size of electrodes that are arranged closely to each other, as well as stray capacitance. These properties lead to many challenges when ranged position tracking application is required, including the application in this research. The sensor in this research is placed away from the keyboard area to avoid obstructions to the pianist. This sensor is required to track human finger across a set of wooden piano keys with 13 cm thickness. On the other hand, current technology of capacitive finger tracking emphasizes either on near proximity sensing or remote gesture recognition, where both of them do not focus on accurate remote positional tracking that is required in this application. As a result, the current researches that embark on piano finger tracking are limited to utilizing sensors that are directly in contact with the pianist, where this method alters the piano playing experience.

Consequently, the purpose of this research is to explore the possibility to track Cartesian coordinate of fingers remotely across the wooden piano key by capacitive sensing method. This could be achieved through a series of research, comparing and designing of a high sensitivity capacitive sensor.

1.5 Research Objectives

The main aim of the research is to design and develop a high sensitivity capacitive sensor that could track finger position on the piano remotely across the wooden obstacles. The goal of this research can be achieved by the following main objectives:

a) To explore the feasibility of non-contact detection of the presence of finger remotely across wooden obstacles based on the change of capacitance.
b) To evaluate the capacitance features as Cartesian coordinate measurements for machine learning using neural network.
c) To investigate the change of capacitance caused by piano key descend and evaluate the dynamics of the sound produced.

1.6 Scope of Work

The scope of work for this research is listed as follow:

a) To prove the validity of this research, a scaled down sensor is proposed. The workspace area of this research is set to be 105 cm^2, which is the area of five keys out of the 88 keys on the piano.
b) To design and develop a high sensitivity capacitive sensor that could detect capacitive change when a human finger touches the wooden piano key with 13 cm thickness. This includes determining the size and arrangement of the electrodes to maximize the sensitivity of the sensor while minimizing noise.
c) The vital aspects in piano playing include finger positioning and the volume of sound produced. The proposed sensor is expected to detect the position of the finger in Cartesian coordinates and determine the sound volume produced by the key press.

1.7 Potential Applications and Contributions of the Research

This research explores the possibilities of detecting minute capacitance change through sensor design and signal processing. With the success of this research, the same methods could be applied to researches that required to detect low capacitance change. There are three main categories that could contribute to the success of this research:

a) Minimizing stray capacitance and environmental noises through hardware design.
b) Differentiating the input signal from the noises through signal processing.
c) Signal training to obtain positional information.

Since each pianist plays the piano differently, this system could be used for storing and preserving a pianist's piano technique. The data of professional pianists could be shared easily through internet, users will have access to the information on how professional pianists apply their unique techniques, which will provide good references for their piano learning. Furthermore, piano technique demonstration from teachers could be stored for their students. The stored data could be reproduced by robots performing on an acoustic piano, potentially recreate the same atmosphere of a live piano performance.

1.8 Thesis Organization

This thesis comprises of eight chapters as described in the following:

Chapter 1 elaborates the overall idea of the remote finger tracking system. Furthermore, this chapter also explains the need of this research that leads to a problem statement of the study. Next, the main objectives of the research are also discussed and finally, the potential applications and contributions of this research is also discussed.

Chapter 2 presents the literature review of this study. An in depth study was made on various areas of current technologies that contribute to the knowledge of this research. The review was first made on available types of sensors that are used for piano playing, and then the review finally focuses on the current technologies of capacitive sensors and the sensor's relationship to musical instruments.

Chapter 3 outlines the methodology which covers the development procedures for the remote finger tracking sensor starting from hardware design of the sensor, interfacing between different devices, signal preprocessing and finally data training

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